Chinese Journal of Aeronautics, (2015), 28(5): 1539–1545

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Surface integrity of GH4169 affected by cantilever finish grinding and the application in aero-engine blades

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Received 3 March 2015; revised 24 April 2015; accepted 6 June 2015
Available online 28 August 2015

KEYWORDS

Blade;
Cantilever;
GH4169;
Grinding;
Surface integrity

Abstract GH4169 is the main material for aero-engine blades and integrated blisks. Because GH4169 has a poor milling performance, the profile precision and surface integrity of blades and integrated blisks are difficult to be met by utilizing the conventional milling process, which directly influence the global performance and reliability of aero-engines. Through grinding experiments on parameters and surface integrity optimization, the helical cantilever grinding process utilizing a 300# CBN RB wheel is presented and applied in finish machining of GH4169 blades. The profile errors of the blade surface are within ±0.01 mm, the roughness is less than 0.4 μm, the residual compressive stresses and the hardening rate are appropriate, there are no phenomena of burr and smearing with the grinding chips, and the leading/trailing edge can be smoothly connected with the suction/pressure surface. All the experimental results indicate that this grinding process is greatly suitable for the profile finish machining of GH4169 blades.

1. Introduction

Blade is one of the most important components for aero-engines and its main rejection factor is fatigue failure.[1,2] Fatigue failures of rotor blades account for more than 50% of major aircraft engine failures. Meanwhile, the finished surface integrity, especially surface roughness and residual stress, has significant effects on the fatigue life of an individual blade and then on the global reliability of an aero-engine.[1] Workpieces with different surface integrity have different fatigue lives of nearly 6 times under certain experimental conditions.[3,4] As one of the most commonly used materials, super alloy GH4169 is widely used for making aero-engine blades and integrated blisks.[5,6] Because of its high-temperature performance, GH4169 has a poor machinability.[7–10] At present, GH4169 blades are machined mainly by numerical control (NC) milling process, which limits further improvement on machining precision and surface integrity because of fast tool wear, cutting chatter, and high cutting forces.[11,12]

It has been proven and focused that high-speed grinding utilizing super abrasive wheels is an effective process on machining GH4169 to improve the precision and surface

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Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2015.06.023
1000-9361

quality.[13–17] At the same time, the fatigue strengths of workpieces can be increased by cubic boron nitride (CBN) grinding process because the finished surface integrity is improved.[18] The line-contact machining and tool path planning methods have been developed, which promote the grinding process widely used in the machining of aero-engine blades.[19,20] Li et al. presents a cantilever grinding process for high-precision machining of aero-engine blades and the profile error of the machined suction/pressure surface does not exceed 0.02 mm.[21] Experimental data is presented by Aspinwall et al. that the root mounting slots of GH4169 aero-engine blisks are machined with profiled electroplated CBN wheels.[13] To sum up the research results, scholars have focused in the fields of grinding temperature measurements, flank grinding mechanism, surface integrity, and high-performance flank grinding wheel. There are very few research results of aero-engine integrated blisks and blade grinding fields because the grinding characteristics and requirements of the application object are very particular. However, the finished surface integrity of aero-engine blades has significant effects on fatigue life and global reliability of aero-engines.

Based on the research results of the cantilever grinding process,[21] an experimental study on the surface integrity of GH4169 aero-engine blades is carried out respectively utilizing a CBN electroplated wheel (EP wheel) and a resin-bonded wheel (RB wheel). Through analyzing the results of the finish grinding surface, the optimal wheel and grinding conditions for grinding GH4169 blades and integrated blisks are presented. At the same time, the results of a verification experiment show that the helical cantilever grinding process utilizing a 300# CBN RB wheel is very suitable for the finish profile machining of GH4169 blades with high precision and appropriate surface integrity.

2. Processing characteristics of cantilever grinding

According to the requirements of the cantilever grinding process for aero-engine blades, different wheel paths are utilized at the stages of rough and finish grinding processes for different purposes. The purpose of the rough grinding stage is to improve the material removing rate and the machining precision. Based on previous research achievements, double machined planes with a symmetrical tool path should be used.

First of all, the purpose of the finish grinding stage is to assure or further improve the machining precision, and then to improve the finishing surface forming rate, while meeting the needs of surface integrity. At the finish grinding stage, the total volume of material removing is small compared with that at the rough grinding stage. The helical tool path should be utilized to machine the blade profile through optimization design of the wheel structure, as shown in Fig. 1, in which F_x, F_y, and F_z are the three components of the grinding force.

A further study is needed to analyze the influence of the grinding force on blade profile precision at the finish grinding stage. Therefore, grinding force experiments are carried out and the radial force is measured because the elasticity modulus of the blade in this direction is the smallest, while the static stiffness is the worst. The experimental conditions are listed as follows.

Material: Nickel-based superalloy GH4169 (solution treatment and ageing), of which the hardness is about HV411, and

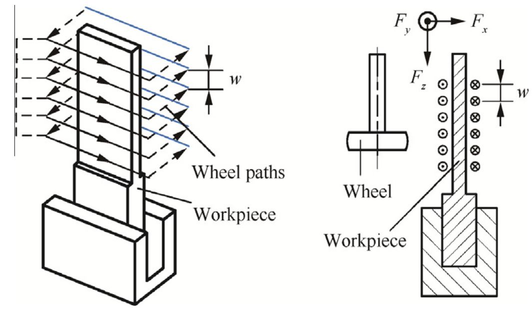


Fig. 1 Helical grinding path and process.

the dimensions of the workpiece are 1.4 mm × 14 mm × 32 mm.

Wheel: The structure of the wheel is shown in Fig. 2, where D is the maximum diameter of the wheel, R_e is the radius of the circular arc generatrix, L_e is the height of the barrel, and d is the diameter of the wheel shaft. CBN EP and RB wheels are utilized, as shown in Fig. 3 in which D = 21 mm, R_e = 20 mm, and L_e = 3.5 mm.

Coolant: Blaser blasogrind high-speed grinding oil.

Under the above grinding conditions, the grinding width w and the radial grinding depth a_e are varied while the grinding speed v_s = 33 m/s and the feed speed v_f = 600 mm/min are held constant. The radial grinding force F_x utilizing the 200# CBN EP wheel is measured by Kistler 9257B and the results are shown in Fig. 4.

From the experimental results, the radial grinding force F_x is very small because small grinding parameters are used at the finish grinding stage. Even when w = 1 mm and

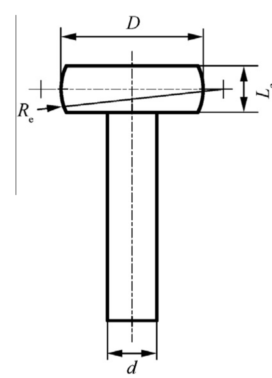


Fig. 2 Structure of the barrel wheel.

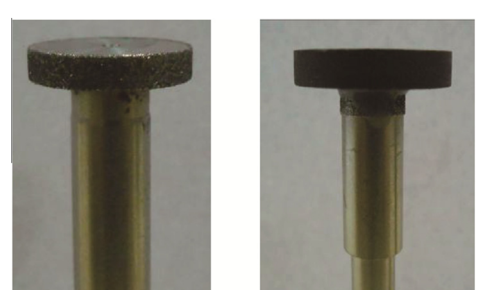
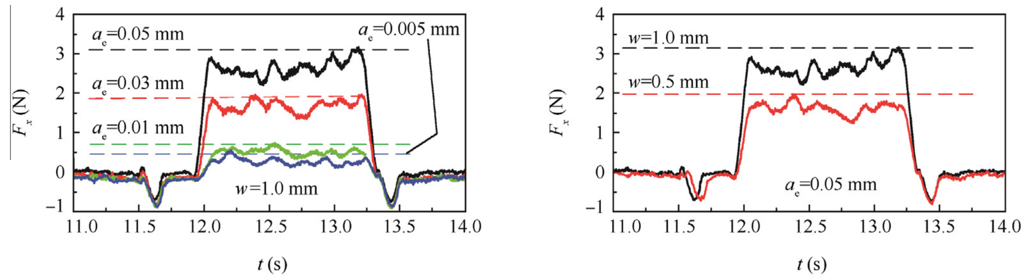


Fig. 3 CBN EP and RB barrel wheels.



(a) Influence of a_e (b) Influence of w

Fig. 4 Influences of grinding parameters on F_x.

a_e = 0.05 mm, the grinding force F_x is less than 3.2 N. Compared with the actual application, the radial grinding depth a_e will not be more than 0.01 mm, which will cause F_x to be smaller than 1 N. Therefore, the elastic deformation caused by F_x will be almost negligible at the finish cantilever grinding stage. Making use of this favourable factor, we believe that cantilever finish grinding can assure or further improve the profile precision of aero-engine blades. Therefore, the purpose of finish grinding is to improve the finishing surface forming rate and meet the needs of machined surface integrity.

3. Cantilever grinding on surface integrity of GH4169

3.1. Influences of the wheel and grinding conditions on surface roughness

Surface roughness is the most fundamental and important indicator of surface integrity, which has a significant influence on fatigue life of a workpiece.[22,23] To optimize the wheel and the appropriate grinding parameters, 140# and 200# EP wheels and a 300# RB wheel are utilized in the experiments considering the great difficulty of manufacturing finish-grained EP wheels. The 300# CBN RB wheel is shown in Fig. 3 and the wheel paths are shown in Fig. 1. Utilizing a Taylor Hobson surface roughness measuring instrument, the roughness in the z direction (perpendicular to the wheel speed direction) is measured, as shown in Fig. 5. Meanwhile, the typical microstructure of finished surface is examined by a scanning electron microscope JSM-6010LA under the grinding parameters of v_s = 33 m/s, a_e = 0.005 mm, and w = 0.5 mm, as shown in Fig. 6.

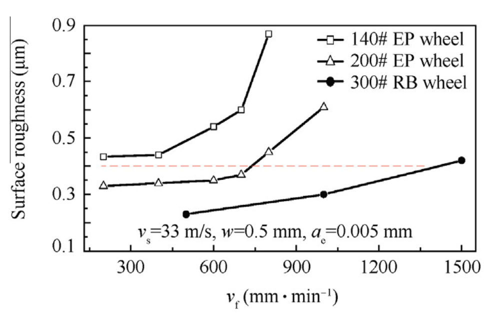
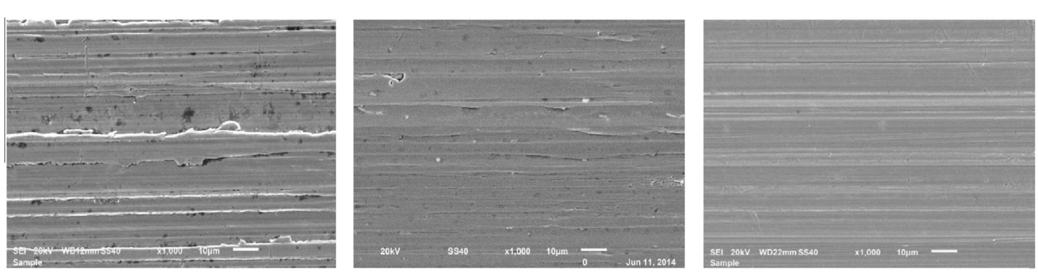


Fig. 5 Influences of wheel and feed speed on surface roughness.

From the experimental results, the 140# EP wheel cannot make surface roughness less than 0.4 μm under the grinding parameters. At the same time, a smearing phenomenon with abrasive dust and burr happens on the finish grinding surface, which reduces the finished surface quality. The surface roughness is less than 0.4 μm under the conditions of utilizing the 200# CBN EP wheel and the feed speed being less than about 700 mm/min. If utilizing the 300# CBN RB wheel, the feed speed can be up to about 1300 mm/min and the finishing surface forming rate is about 2 times of that utilizing the 200# CBN EP wheel. Meanwhile, there is no significant defect on the finished surface.

3.2. Influences of the wheel and grinding conditions on surface hardening

Surface hardening is another important indicator of surface integrity as it has a positive influence on wear resistance and corrosion resistance. Therefore, surface hardening experiments are carried out and the microhardness of the finish grinding surface is measured, as shown in Fig. 7. The grinding



(a) 140# EP wheel and v_f=600 mm/min (b) 200# EP wheel and v_f=600 mm/min (c) 300# RB wheel and v_f=1000 mm/min

Fig. 6 Influence of wheel on surface morphology.

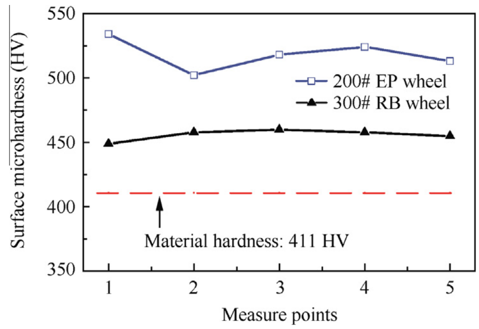


Fig. 7 Influence of wheel on surface microhardness.

conditions are using the 200# CBN EP wheel, v_s = 33 m/s, a_e = 0.005 mm, w = 0.5 mm, v_f = 600 mm/min, and using the 300# CBN RB wheel, v_s = 33 m/s, a_e = 0.005 mm, w = 0.5 mm, v_f = 1000 mm/min, respectively.

From the above results, we can know that the average hardness of the finish grinding surface utilizing the 200# CBN EP wheel is about HV538 while that of the base material is about 411 HV. Compared to the initial material, a hardening rate about 26% is achieved through the finish grinding. This conclusion coincides with the previous research result. However, the average hardness of the finished surface will be about HV456 if the 300# CBN RB wheel is used, and the hardening rate will be reduced to about 10.95%. According to the research status, a clear conclusion that the fatigue life of a workpiece increases or reduces with the surface hardening rate cannot be achieved. Therefore, as for the present, we believe that a low hardening rate will be beneficial to the fatigue life of a workpiece because it can be guaranteed that the fatigue life of the workpiece cannot be significantly reduced at least.

Moreover, the morphology of the cross section in the two directions (perpendicular to and along the wheel speed direction) is examined under a scanning electron microscope, as shown in Fig. 8.

The results show that the grains, even very close to the finished surface, are not distorted and elongated in the two directions when utilizing the 300# CBN RB wheel. In addition, very little plastic deformation on the finished surface is the reason that the surface hardening rate is low.

3.3. Influences of the wheel and grinding conditions on surface residual stress

Surface residual stress is another important indicator of surface integrity. Many research results indicate that a proper surface residual compressive stress can suppress fatigue crack initiation and growth so that the fatigue life of a workpiece can be improved.[1,3,23] However, a quantified or optimal range of the surface residual compressive stress is very difficult to provide and its associated research results are few. Therefore, comparative grinding experiments with GH4169 are carried out utilizing the 200# EP wheel and the 300# RB CBN wheel respectively. The surface residual stresses in both directions are also observed by X-ray analysis, as shown in Fig. 9, in which σ_H is the surface residual stresses.

From the above results, the surface residual stresses in both directions are compressive when utilizing both kinds of wheel because of short contact length and low grinding temperature.[24,25] Meanwhile, their absolute values decrease with increasing the wheel speed v_s. However, their variation ranges are small and the absolute values of surface residual stresses in two directions utilizing the 200# EP wheel are bigger than those utilizing the 300# RB wheel under the same grinding conditions. Meanwhile, whichever kind of wheel is utilized, the absolute value of the surface residual stress in the wheel

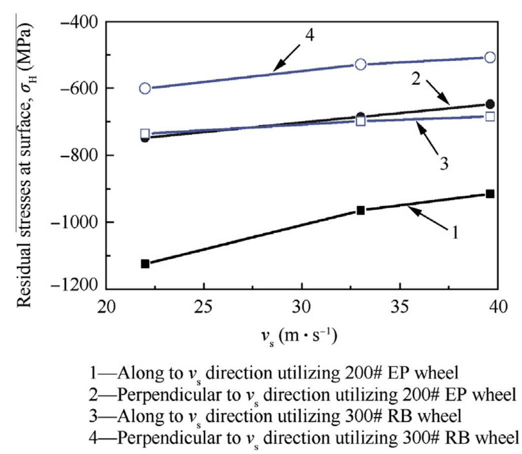
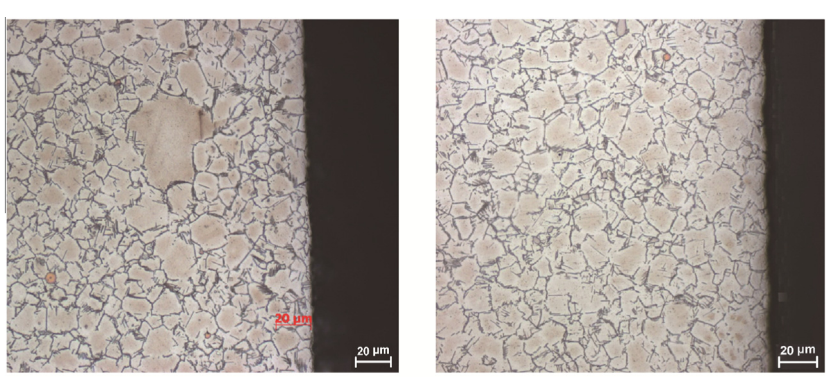


Fig. 9 Influences of wheel and grinding speed on surface residual stresses.



(a) Along to the wheel speed direction (b) Perpendicular to the wheel speed direction

Fig. 8 Cross-section microstructure in two directions.

speed direction is bigger by comparison. The experimental results also indicate that the surface plastic deformation formed by the 300# RB wheel is smaller, which is the reason that the absolute values of the surface residual stresses are smaller than those utilizing the 200# EP wheel.

According to the above results and the previous research achievements, appropriate residual compressive stresses can suppress potential risks in terms of crack initiation, propagation, and fatigue failure of end products.[25] However, excess compressive stresses will cause plastic deformation on the blade surface easily when the blade is suffering an alternating load.[26] Therefore, we believe that the surface residual compressive stresses formed by the 200# EP wheel are too big for the finish grinding surface and the absolute value in the wheel speed direction is close to the tensile strength limit (about 1350 MPa) of GH4169. Utilizing the 300# RB wheel, appropriate residual compressive stresses in both directions (about −700 MPa and −540 MPa, respectively) can be achieved on the finished surface by chance with the wheel speed v_s from 33 m/s to 40 m/s.

4. Finish grinding example with aero-engine blade

Utilizing the following grinding conditions and parameters, finish grinding examples with GH4169 aero-engine blades are carried out on a high-speed machine tool, as shown in Table 1. The length of this blade is about 41.0 mm and the maximum length of the chord line is about 44.0 mm. The maximum value in the width is about 1.4 mm. Meanwhile, the profile precision

Table 1 Experimental conditions and grinding parameters.

Item	Description
Workpiece	GH4169 aero-engine blade
Rough grinding process	Double machined planes with the symmetrical tool paths[21]
Rough grinding conditions	200# EP CBN wheel, $D = 21$ mm, $R_e = 1.5$ mm. Coolant: Blaser blasogrind grinding oil
Rough grinding parameters	$v_s = 33$ m/s, $a_e = 0.02$ mm, $w = 2$ mm, $v_f = 600$ mm/min, 4 times rough grinding
Finish grinding process	Helical cantilever grinding process
Finish grinding conditions	300# RB CBN wheel, $D = 21$ mm, $R_e = 20$ mm. Coolant: Blaser blasogrind grinding oil
Finish grinding parameters	$v_s = 33$ m/s, $a_e = 0.005$ mm, $w = 0.5$ mm, $v_f = 1000$ mm/min, twice finish grinding

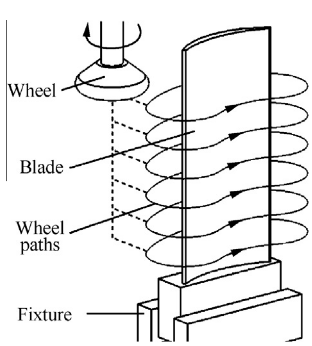


Fig. 10 Schematic diagram of the helical finish grinding path and process.

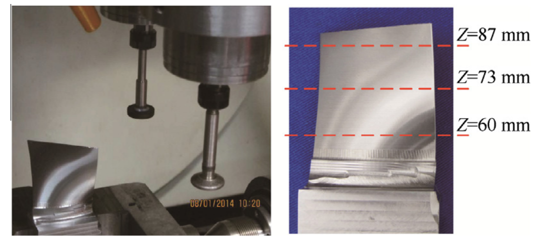


Fig. 11 Blade in grinding and locations of cross-sectional curves to measure.

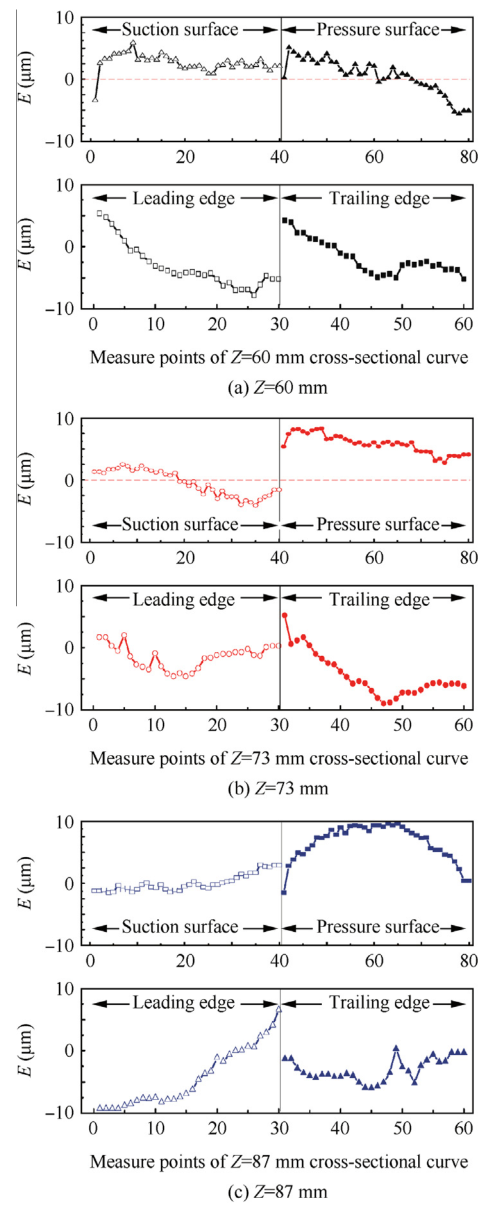


Fig. 12 Measurement results of cross-sectional curves.

and the surface integrity after finish grinding are measured to prove the above analysis and study correctness and effectiveness. The experimental grinding path and process are shown in Fig. 10. After 4 times rough grinding and twice finish grinding, the aero-engine blade and the measured profile errors are shown in Figs. 11 and 12, respectively. In Fig. 11, Z represents the axial direction of grinding. In Fig. 12, E represents the contour error.

From the measurement results of three cross-sectional curves, we can know that the profile absolute errors of the blade surface including the leading/trailing edge are fluctuant in the range of ± 0.01 mm under the conditions of the helical cantilever grinding process and utilizing the 300# RB wheel. Meanwhile, small wear and high profile retention of the RB wheel can be proven in the finish grinding process, which are the reasons that the blade has a very high profile precision.

The blade surface and edge are examined under a scanning electron microscope, as shown in Figs. 13 and 14. Simultaneously, the finished surface roughness is about 0.31 μm.

The surface residual stresses are measured in the middle of the suction/pressure surface. The average values are about 700 MPa and 540 MPa in two directions, respectively. In summary, the surface quality of blade surfaces is stable and no defect phenomenon happens on the finished surface. Most important of all, the leading/trailing edge can be smoothly connected with the suction/pressure surface and has a high profile precision, which shows clearly that the helical cantilever grinding process utilizing the 300# CBN RB wheel is very suitable for the profile finish machining of GH4169 blades. Meanwhile, moderate surface integrity can be achieved.

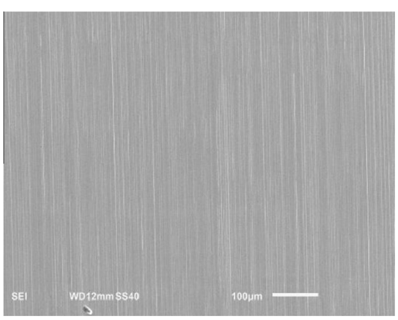


Fig. 13 Surface morphology of the blade machined utilizing the 300# RB wheel.

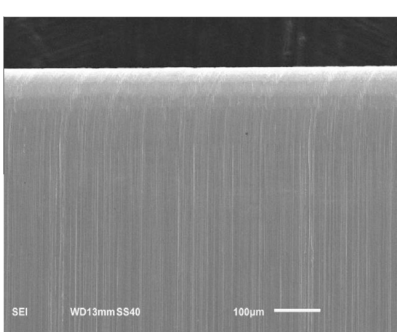


Fig. 14 Smooth connection of the leading/trailing edge.

5. Conclusions

(1) Under the conditions of the helical cantilever grinding process and utilizing a CBN wheel for finish machining of GH4169, the radial grinding force F_x is very small and less than 1 N. Even when utilizing grinding parameters of $v_s = 33$ m/s, $w = 1$ mm, $a_e = 0.05$ mm, and $v_f = 600$ mm/min, the grinding force F_x is less than 3.2 N. Therefore, the elastic deformation caused by F_x will be almost negligible at the finish cantilever grinding stage.

(2) Under the same grinding conditions, the finished surface roughness is very different if utilizing 140# and 200# CBN EP wheels and a 300# CBN RB wheel. If utilizing the 200# CBN EP wheel and other given grinding parameters, a feed speed of less than 700 mm/min can make the surface roughness less than 0.4 μm. However, if utilizing the 300# CBN RB wheel, the feed speed can be up to about 1300 mm/min.

(3) The surface hardening is severe and the surface residual compressive stresses are too big for the finish grinding surface if utilizing the 200# CBN EP wheel. Utilizing the 300# CBN RB wheel, the hardening rate is reduced to 10.95% and appropriate residual compressive stresses about −700 MPa and −540 MPa in two directions respectively can be achieved.

(4) The experimental results with GH4169 aero-engine blades show clearly that the profile errors of the blade surface including the leading/trailing edge can be achieved in the range of ± 0.01 mm if utilizing the helical cantilever grinding process and the 300# CBN RB wheel. The surface roughness can be less than 0.4 μm and the leading/trailing edge can be smoothly connected with the suction/pressure surface. Meanwhile, moderate surface integrity can be obtained. All the experimental results can meet the requirements for finish machining of GH4169 blades.

Acknowledgements

The authors thank the anonymous reviewers for their critical and constructive review of the manuscript. This study was co-supported by the National Natural Science Foundation of China (No. 51105024) and the National Science and Technology Major Project of China (No. 2013ZX04001051).

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